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This is the Final Technical Report of work supported by a grant entitled "The dynamics of visual representation: Attention, encoding, and retrieval processes." After a section describing the objectives of the work, the report provides a synopsis of the principal accomplishments, in five categories: (1) Investigation of the relation between location-probe and probed-reciting paradigms, to test whether the transformations that underlie performance changes with probe delay in the two paradigms are the same or different. (2) Investigation of the transformation associated with the location-probe paradigm (3) Extensive work with the probed-reciting paradigm at zero probe delay, manipulating the legibility of the displayed characters as another approach to studying the transformation required for response. (4) Application of variants of a traditional visual search paradigm to investigate effects of properties of the early representation on the order of search, again by manipulating legibility. (5) Development of new tests of stage models of mental operations.

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1. Objectives and Background

The objective of this research is to investigate how visual information is represented internally during the first few seconds after a display. Issues include (1) how many representations must be postulated, when they are available, and what their properties are, (2) how the transformation from one to another is accomplished, and (3) the mechanisms by which information from them is selected and retrieved. Unlike much previous research on these issues, our research employs arrays small enough so as not to overload the system: we seek to understand performance under conditions of high accuracy.

By applying time pressure to the subject under these conditions we induce mechanisms to reveal themselves, not by how they fail, but by how much time they need to succeed. Thus we measure how much time a person needs to retrieve information accurately from his or her representation of an array (of alphanumeric characters or nameless shapes, for example), and how this latency of retrieval (or reaction time, RT) depends on time since display, number of displayed elements (array size, s), and information required. A critical feature of our approach is the use of a range of s-values. Two of the reasons why this feature seems essential are : (1) It protects against erroneous generalization. (For example, we have found that whether retrieval requires more or less time as the probe is delayed depends on s.) (2) The function that relates retrieval latency to array size, $RT(s)$, and especially changes in that function with probe delay, provide considerable analytic power.

In earlier work we had developed and tested four diverse experimental paradigms that express this approach:

(a) *Location Probe (LP)*. The probe, usually a visual marker (but sometimes tactile), specifies a location; the response is to name the element that is or was in that location.
(b) *Identity Probe (IP)*. The probe, usually a spoken name (but sometimes visual), specifies the identity of a target element; the response is to name the element in the array to the right of the target.
(c) *Probed Reciting (PR)*. The probe, a tone burst, specifies direction; the response is to recite the entire array in that direction.
(d) *Location-Specific Matching (LSM)*. The probe is a visual *target* element that also marks the location of a *test* element within the array; the response is "yes" or "no", depending on whether target and test elements match.

All four paradigms produce orderly data that reveal sharp changes in the pattern of retrieval times — and hence in the internal representation — within about one sec of the display. (The methods include matching, naming of single elements, and reciting of sequences; information to be retrieved is designated by identity, location, or order.) Among the more surprising findings are inverse effects of delay on search rates and reciting speed, rapid loss of a property of direct access by location, suggesting change from a *random-access memory* to a *sequential-access memory*, functional equivalence of visual and tactile location markers, and an advantage of array over sequential presentation even after several seconds.

2. Principal Accomplishments

We have been concentrating on five areas within the proposed research: (1) We investigated the relation between location-probe (LP) and probed-reciting (PR) paradigms further, to test whether the transformations that underlie performance changes with probe delay in the two paradigms are the same or different (Sections 2.1-2.2). (2) We investigated further the transformation associated with the LP paradigm (Sections 2.3-2.6). In domains (1) and (2) there has been a good deal of software development, for preparing experimental materials, for running experiments, and for data analysis, along with exploratory and formal experiments. (3) We have worked extensively with the PR paradigm at

zero probe delay only, manipulating the legibility of the displayed characters as another approach to studying the transformation required for response (Section 2.7). (4) We have used variants of a traditional visual search paradigm to investigate effects of properties of the early representation on the order of search, again by manipulating legibility (Section 2.8). (5) And we have pursued an issue that is basic to most of the methods we and many others use: that of testing the assumed selectivity of effects of experimental manipulations on component processes and the additivity of the durations of those processes (Section 2.10).

2.1 Relations between the visual transformations revealed by location-probe and probed-reciting paradigms

Earlier data had suggested close similarity between the time courses[1] of the transformations revealed by location-probe (LP) and identity-probe (IP) paradigms, measured in the same subjects. Furthermore, the total time required by the transformation in the probed reciting (PR) paradigm was close to the total for the others, within the precision of our comparison, which was limited because this comparison had been made between subjects.

However, details of the estimated time course of the transformation differed for PR versus the other paradigms, and whereas LP and IP data tended to favor a process that occurs in parallel over array elements, there was persuasive evidence for a serial component in the transformation indicated by PR. For these reasons it seemed critical to investigate the relations between the transformations associated with PR and LP, and to do so within subjects.

The method we used was to compare control conditions in which LP and PR paradigms were used separately, with an experimental LP-PR condition in which they were mixed under uncertainty. In the mixed condition, the subject sees an array (array size varied from trial to trial) and then, after a delay (varied from block to block), randomly either sees a location probe and responds with the name of a single element, or hears a tone and responds by naming all the elements in sequence. We expected one of two sets of outcomes. (a) If the two transformations are the same, then we should find evidence of sameness of time-course, and performance in the mixed condition at each probe delay and for each paradigm should look the same as in the corresponding single-task control condition, except possibly for an effect of mixing (and having to discriminate the two kinds of probe) on the intercepts of the functions that relate mean RT to array size. (b) If the transformations are different, then we should find evidence for time-course differences, and performance on at least one of the tasks in the mixed condition should suffer when the probe is delayed, because either the choice of transformation is deferred during the probe delay and until the probe type is discriminated, or because, on some trials, the wrong transformation is initiated.

Results indicated, first, that subjects can handle the mixed task smoothly. Second, the within-subject comparison made it clear that the time courses of the transformations associated with the two paradigms differed markedly (consistent with outcome b), with the one associated with the LP paradigm taking longer. However, performance in the mixed condition with each probe type was very similar to performance in the corresponding pure control condition (consistent with outcome a). Our conclusion is that whereas the transformations differ, they are not incompatible. Suppose that the transformation called for in the PR paradigm involves two separate and successive operations (which we denote $T1$ and $T2$) performed on the full set of array elements. For example, $T1$ might include the extraction of contours, while $T2$ might include identification and response preparation. The transformation called for in the LP task might require just the first of these operations, $T1$, to be applied to the full set of array elements; regardless of array size, $T2$ would have to be applied only to the single element in the location specified by the probe, so would be reflected in the intercept (but not the slope) of the $RT(s)$ function. $T1$ could be parallel over array elements, while $T2$ is serial. This proposed relationship

1. In this context the time course of a transformation is defined by the function that relates the percentage of total (asymptotic) change achieved to probe delay.

between the two transformations explains the existence and direction of the time-course difference, and the absence of any decrement due to probe uncertainty. In what follows we refer to $T1$ as the "initial transformation."

Because the experiment involved a mixture of two tasks in some conditions, the program to generate stimulus materials — here the displayed element sequences (and the probed location in the LP task) — was entirely rewritten. Because the design also called for balancing of up to 5 trial dimensions, the new program was complex (about 2000 lines of code in C). However, we regard this major effort as worthwhile, especially for experiments in which subjects are practiced for many days, partly because without adequate balancing and randomization they can learn to anticipate properties such as which of the two kinds of response will be required, or which location will be probed; it is critical for for success of the experiment that they be unable to anticipate such trial properties.

2.2 Influence of reciting direction on LP performance in the PR-LP mixture

We already know that the slope of the $RT(s)$ function in the PR task is greater when reciting is from right to left (backwards) than forwards. This can be explained by the idea that the serial transformation process that precedes the vocal response (possibly $T2$ above) depends on the direction that reciting will ultimately take, and, in particular, that the order in which array elements are transformed is controlled by the order of reciting, and is hence under experimental control. If this is so, then whether or not the LP and PR transformations are the same, we might see an effect of reciting direction on LP (non-reciting) trials that are mixed randomly with PR trials in the LP-PR mixture, at intermediate delays. (At such delays, only elements early in the reciting order would have been transformed by $T2$, and a transformed element might produce a faster LP response.) Thus the LP performance might serve as a sensitive indicator of the transformation state of individual elements. Indeed we found such an effect when we compared the slopes of the serial-position curves for LP trials in LP-PR blocks in which reciting direction was always either forward or backward. To eliminate biases in eye position as a cause, we developed a procedure in which the required reciting direction was varied randomly from trial to trial, signaled by a salient visual cue concurrently with the brief display; the effect on LP trials was the same. Finally, if the transformation time per element is increased (by degradation of the array) we expected the left-to-right differential on LP trials to increase, and found indeed that it did.

2.3 Results from a double location-probe procedure: A test of direct access and its disappearance, with array-size fixed

One approach that has helped to clarify the change in retrieval mechanism in the LP paradigm is to present two probes, simultaneously or with a small delay, and require a pair of responses, giving the spoken names of the elements in the two positions probed. Of special interest is a *proximity effect*, the effect of the spatial separation of the two probes on the increment in retrieval time associated with the second element retrieved, which perhaps incorporates a "shift of attention" from the first location accessed to the second. We developed the software for such a procedure and began data collection, with very promising results. It would be consistent with inferences from our earlier findings with a single probe (and the idea of direct access by spatial position) if the proximity effect was relatively small when the pair of probes was presented close in time to the array; this property of the representation might change as the pair of probes is delayed, with the delay providing time for the transformation being studied to proceed.

This is exactly what we found: The two probes were separated by 100 msec., and the array contained six elements. When the first probe was presented 50 msec before array onset, there was essentially no effect of spatial proximity: the average effect of increasing the separation by one element was only 1 msec. When the first probe was presented 650 msec after array onset, the RT increased by about 28 msec for each element between the two elements probed, a large effect, and a large difference as caused by the probe delay. We found similar effects, but less orderly ones, when the two probes were presented simultaneously. One important feature of this finding flows from the fact that it is not a change, with probe delay, in the effect of the *size* of an array, as are many of the effects we have been studying. Interpretation of such array-size effects requires one to consider the possible effects of an increase with delay in the dependence of memory load on array size, as well as the possibilities that

interest us more: a change in basic properties of the visual representation. The proximity effect is measured with a fixed array size, so its increase with delay cannot be explained in this way, which facilitates its interpretation.

2.4 Coordinate frame for location information

A possibility often considered is that one difference between early and later representations of visual information is in the coordinate system to which it is referred, with absolute or retinotopic coordinates early, and relative or spatiotopic coordinates later. In earlier work using the LP procedure we showed that the direct-access property found for the early representation is convincingly demonstrated by both tactile and visual probes. This might seem to suggest that direct access is not contingent on the use of absolute coordinates, but the result is not decisive for this conclusion, since it is possible that the response to a *tactile* probe is *mediated* by absolute visual location early, and by relative visual location later.

Our principal new approach to this problem was to probe for an element by specifying its absolute or its relative location at different delays. In the normal LP procedure the probe combines both kinds of information. Absolute location is represented by the relation between the probe and the fixation point; relative location is represented by the relation between the probe and the registration marks that appear with the array, above and below each occupied location, and remain until the response. In a pure relative-location variant, the registration marks are removed, and then reappear in a (possibly) different set of contiguous absolute locations, along with the probe. In an absolute-location variant, the registration marks do not reappear, so the probe can be interpreted only by using its location in absolute space, relative to the fixation point.

To our surprise, preliminary results indicate that after practice the slope of the function relating mean RT to array size is invariant over the normal procedure and the two variants. There is, however, an intercept difference, whose interpretation has to be considered: If computations were required to get from one coordinate system to another, but their duration was independent of array size, then they would be hard to detect with our method. The suggestion from these initial data, however, is that at long delays, relative and absolute location are equally useful as retrieval cues. Although detailed examination of the data patterns provides no basis for suspecting an effect of probe type on the kind of representation that is formed, one could better guard against this by mixing the three kinds of probe within the same trial series.

2.5 Effects of concurrent articulation on the initial transformation

In several pilot experiments and two formal experiments we have studied the effects of concurrent articulation on the transformation associated with the IP and LP paradigms. The method was to have subjects start articulating a recycling sequence before onset of the display, and continue through the probe delay until just before the probe (first experiment), or until the actual response (second experiment).

In numerous experiments on short-term memory for information in visual displays, concurrent articulation (CA, sometimes called "articulatory suppression") has been found to impair recall. Furthermore, several effects attributed to the operation of the "articulatory loop" in encoding and retaining information are reduced or eliminated by CA. One example is the phonological similarity effect: without CA, recall accuracy is lower for sequences composed of phonologically similar letters than for sequences composed of phonologically dissimilar ones. CA diminishes recall for both types of sequence, but especially for sequences composed of dissimilar letters, thus reducing or eliminating the phonological similarity effect. That is, there is a negative interaction between CA and phonological similarity. The most prevalent interpretation of CA effects is due to Alan Baddeley: (a) covert articulation is required to encode visually presented characters and perhaps to maintain the information in memory, and (b) CA reduces or eliminates covert articulation. The relationship to phonological similarity is explained by arguing that covert articulation is less effective for phonologically similar sequences, so interfering with it impairs recall of such sequences less.

Given Baddeley's account of CA, one would expect that it would interfere with the transformation under study. Given such interference, and no great increase in the number of errors, one would expect

that the slopes of the functions relating mean RT to array size in the location-probe and identity-probe paradigms would increase with probe delay at less than the normal rate. It was this expectation that we set out to test. Because we wanted to use our usual vocal responses, and CA is also vocal, we encountered some technical difficulties that had to be surmounted. In the first study we measured the effect of CA on both the location-probe and identity-probe paradigms. Subjects had to stop CA before the probe, and the response to the probe had to be substantially louder than the CA. At the end of the experiment we tested for the phonological similarity effect, as a way of "calibrating" our CA. We found the expected interaction between phonological similarity and CA: Even in our highly-practiced subjects, CA produced a decrement in the memory span for letters, and one that was greater for dissimilar letters. The effect of CA on the transformation was small, however, and became smaller with practice, contrary to expectation.

In none of the studies of CA that we know of has the CA performance itself been measured quantitatively. Given the negative results of the first study, we felt it was important to in the second study to measure the rate of CA under control conditions (CA alone) as well as experimental conditions (CA with a display that had to be retained and a probe of information in that display). We developed a method for doing this with the CA consisting of a repeated disyllabic nonsense word beginning with a stop consonant. (See Section 2.6.) Also, we wanted a procedure in which, in the CA condition, we could minimize the time between the display and the probe, time during which the subject was not articulating. To achieve this we developed a "talk-through" procedure, in which the (loud) response to the probe emerged from the (softer) CA with a time gap that we enforced to be no more than 100 msec. Using this method we found that the CA rate was remarkably stable over trials, and remarkably similar for experimental and control conditions.

In our second study we used this method, and only the location-probe paradigm. We again found that the effect of CA, evident early in the experiment, virtually disappeared with practice. At the end of the experiment, we again found that the CA the subjects had practiced for several hours still created a substantial decrement in memory span for letter lists. However, this time we did not find the interaction between CA and phonological similarity.

From our viewpoint the most interesting interpretation is that although the transformation can make use of covert articulation (as it seems to have done early in the experiment), subjects can learn to perform the transformation without it. The fact that after considerable practice, CA still produced a decrement in memory span shows that it was still potent. On the other hand, the fact that we failed to demonstrate an interaction between CA and phonological similarity could mean that the interfering effect of CA had changed, even though it had not disappeared.

2.6 Improvements in measurement of spoken responses

We have devoted a good deal of effort to improving the precision of our measures of vocal response latency and duration. The most significant of several modifications of the experiment-running code is the addition of storage of detailed records of subject utterances in a form that permits rapid analysis. In the past, we have filtered the speech in high-frequency and low-frequency bands, and the energy in each of these bands has been measured for each 10-msec epoch. A threshold has been applied in each band, and the utterance is deemed to have started when the first run of specified length of 10-msec epochs is detected. A similar decision rule has been used for determining when the utterance ends. (We have also stored a measure of peak level in each band.) However, this method requires us to commit ourselves to particular values of threshold and run length before the experiment, rather than adjusting these parameters to particular subjects, based on characteristics of their speech. The alternative of storing a complete digital record of the speech at a sampling rate of, say, 10kHz, would consume too much space. The compromise we selected is to store the energy levels in each 10 msec epoch for each of the two bands. This record allows us optimally to determine what parameters to use within our speech timing algorithm. It also permitted us to measure the rate of CA, as discussed in Section 2.5.

2.7 Encoding multi-character arrays for identification

It is surprising how little is known about the time course of the identification of characters in multi-character arrays. Matching and search tasks can probably be accomplished without full

identification, so may not be directly relevant, as was pointed out by Pashler & Badgio (1985). It is partly for this reason that the paradigms used in the present project have typically called for naming of array elements. In almost all the work we have used the PR (probed-reciting) paradigm, with the subject having to respond with zero probe delay. Instead of measuring the time course of the transformation by examining performance at different probe delays, we have tried to influence the time course by varying the legibility of the displayed digits. We have used two kinds of degradation: In one, a grid, or pattern mask (PM) is superimposed on the digit. In the other, rotation and reflection (RR), the digit is reflected about its vertical axis and rotated 180 degrees. (Unlike rotation alone, the effect of RR on identification time is large and persists over ten or twenty hours of practice.)

Some of this work was reviewed in a paper given at the annual meeting of the Psychonomic Society in November 1992 in which we introduced a parallel-serial two-process model of character identification; a transcript is submitted as an appendix of the present report.

The model can be summarized as follows:

1. There are (at least) two processes associated with character identification,
1A. One process (α) can operate in parallel across elements. It is influenced by PM degradation.
1B. Another process (β) operates serially across elements. It is influenced by RR degradation.
1C. The α process preceded the β process.
2. Within a single element, processes α and β operate sequentially.
3. Processes α and β for different elements can overlap in time.
4. In the PR paradigm, the order of occurrence of the β processes for different elements may correspond to the order of report.

Comment: The α process may correspond to what is sometimes called "pre-attentive processing," because it occurs early and in parallel over the visual field. It may achieve the extraction of task-relevant contours. The β process may refer the extracted form to memory representations. It is possible that α corresponds to $T1$ and β to $T2$ (Section 2.1).

We have used two principal paradigms in exploring the effects of PM and RR degradation: In "homogeneous degradation" (akin to the method of Pashler & Badgio, 1985) all elements are either intact (normal) or degraded, and we vary the number of such elements (array size). In "factorial degradation," (related to a method discussed by Egeth and Dagenbach, 1991) array size is fixed, and we vary the number of degraded elements. One can regard these two paradigms as "diagnostics" for serial versus parallel processes: in earlier work by others, for example, a finding such as "the effect of PM on different elements is underadditive," or "the effect of PM in the homogeneous paradigm is the same, regardless of array size," or "the effect of PM in the factorial paradigm is the same, regardless of the number of degraded elements," would lead to the conclusion that "character identification occurs in parallel." Alternatively, additive or proportional effects would lead to the conclusion that "character identification occurs serially." That this kind of inference is oversimplified is revealed by our finding both results in the same task, depending on type of degradation (PM versus RR). Hence our more complex model described above.

Data collected early in the grant period, using the homogeneous paradigm, supported Assumptions 1A and 1B. Later in the grant period we performed experiments using the factorial paradigm, also supporting the same assumptions. In experiments involving a single element, in which the two kinds of degradation were applied factorially (no degradation, RR only, PM only, both RR and PM) we observed additive effects of RR and PM, supporting Assumption 2. In experiments using displays consisting of two elements side by side, with instructions to recite the elements left-to-right, we obtained evidence supporting assumptions 1C, 3, and 4.

One of the more interesting outcomes of this work results from the property described as Assumption 3. For example, suppose that the array consists of two elements side by side, indexed 1 and 2, and reciting is left to right. Then PM applied to the element 2 has a substantially smaller effect on reaction time than PM applied to element 1. This is explained by the β processes for the two elements

being serial and ordered β_1 then β_2 (Assumptions 1B, 4), and by the fact that α_2 (the process prolonged by a right-hand PM) can operate at the same time as β_1; the effect of the PM on α_2 can therefore be partially or fully *hidden* by β_1. In contrast, because β_1 must await completion of α_1 (Assumption 2), the effect of the left-hand PM is fully reflected in the reaction time, rather than being hidden. Thus the overlap property (Assumption 3) means that manipulations of the parallel process (α) can reveal the seriality and ordering of a serial process (β) that follows it. Since the work of Townsend it has been recognized that data patterns consistent with a serial process may also be consistent with a "limited-capacity" parallel process — one in which the duration of an operation varies inversely in a particular way with the number of operations. The finding that the effect on α_2 can be hidden by β_1 argues against the parallel-process interpretation of process β, and favors the serial-process interpretation.

2.8 Guidance of visual search by relative legibility

We have conducted several pilot studies and two formal experiments, with a third in progress, on the role of legibility differences in determining the order of visual search.

The paradigm is one in which one or more target digits are specified, and an array of digits then briefly displayed; the subject makes a response as fast as possible, naming a target if it is present in the display (positive response), and saying "no" otherwise (negative response). (We used target naming as the positive response, even with only one target specified, rather than utterance of the word "yes" or pressing of a key, in anticipation of experiments with two targets in which both could be present in the array; we wanted a way to determine which target element the subject found first.) As array size is varied in such experiments, and so long as targets and nontargets are drawn from the same ensemble, mean reaction time (RT) increases linearly with array size, and often with a 2:1 slope ratio for the functions for negative versus positive responses. This suggests a target-comparison process that is serial over elements in the array, and self-terminating (positive response initiated upon occurrence of a match of target to array element).

Earlier work (Experiment 1) had suggested, surprisingly, that reducing the legibility of the nontarget in a two-element array that contained the target could actually speed the positive response. If the processing of the display contains an *encoding process*, possibly in parallel over elements, followed by a *target-comparison* process, presumably serial over elements, then the legibility effect could be explained if a legibility difference that affected the encoding process could influence the order of the target-comparison process. The hypothesis, then, is that focal attention tends to shift to the more legible of two elements.

In the first of the recent experiments we used single targets and arrays of size 1 and 2 only. Elements were either intact, or degraded by a superimposed grid. (This is the same pattern mask — PM — as has been used in the experiments on character identification described in Section 2.8.) Data on the nontarget trials in such experiments appear paradoxical. They have three features:
(1) RT increases from array size 1 to array size 2. This suggests that one or more of the operations on elements are serial.
(2) The effect of degrading both elements in a two-element array is substantially less than twice the effect of degrading one element in a one-element array. This suggests that the grid influences an operation that is parallel over elements.
(3) RT increases as the number of degraded elements in a two-element array increases from zero to one, and also from one to two. This is the paradoxical result, as it suggests that the grid influences a process that is serial over elements. A clue to resolve the paradox lies in the following results from the positive trials.
(4) Suppose the target element is intact. Then the effect of degrading the nontarget element is to speed the positive response. Similarly, if the target element is degraded, the effect of degrading the nontarget element is to speed the response. This is the type of finding that suggests that the more legible element attracts attention, such that the self-terminating serial target-comparison process tends to start with that element.

We are tempted to conclude that an initial encoding process that is parallel over elements, and affected by PM (possibly "pre-attentive," and achieving the extraction of relevant contours) guides the subsequent serial target-comparison process. By itself, however, this account does not explain finding

(3), for arrays that contain no target. If a parallel encoding process for all elements in the array had to be completed before the serial target-comparison process could begin, then we would expect that degrading both of the two elements would have approximately the same effect as degrading only one. Suppose, however, that the target-comparison process for one element in a two-element display can overlap the encoding process for the other. (Note the similarity of this aspect of the model to Assumption 3 in our model for character identification.) For example, if we degrade element 1, then its encoding process is prolonged. But if element 2 is intact, and the target-comparison process starts there, then some or all of the prolongation may not be reflected in the RT, because it will be *hidden* by the target-comparison process for element 2. On the other hand, if both elements in the array are degraded, the full prolongation of the encoding process is reflected in the RT. Thus the overlap property permits us to explain finding (3). Without making an inference from finding (4) for positive responses, however, or appealing to a more quantitative analysis of RTs for negative responses, we cannot conclude that legibility differences guide the order of the target-comparison process. Qualitatively, finding (3) could be explained if the order of comparisons was fixed before the array appeared, and on half of the trials with one element degraded it happened to be the second element to be tested against the target. However, fitting several quantitative models to the data from this experiment supports the idea of relatively strong determination of the order of comparisons by relative legibility.

To gain more "direct" evidence we developed our Experiment 3, in which two targets were specified on each trial. On most trials either no target was present in the array (negative response, "no", required) or one target was present (positive response - naming the target - required). But on some trials with two-element arrays, both targets were present. The subject was told to name just one of the targets if both were present, whichever one he or she encountered first. The critical trials were ones in which one element was degraded and the other intact. Our theory, based on the earlier results, suggested that there would be a strong tendency to name the intact element rather than the degraded one, and this is what we found.

Also in the second experiment we tested an alternative to the legibility hypothesis. In Experiment 1, degraded elements had been brighter (added mask), and in Experiment 2, the degraded elements were dimmer (fixed mask for all elements, dimmer digit on which it was superimposed). In each experiment it is possible that subjects learned the correlation between brightness and legibility, and that search was guided by brightness. In Experiment 3 degradation was achieved in two different ways, randomly from trial to trial, either by brightening the grid or dimming the digit. Nonetheless, both types of degradation had the expected effect, both on time to find the target when one target was present, and on choice of target when both were present. With each type of degradation in this experiment there were a total of about 765 trials with a display of size 2 on which two targets were displayed with one degraded, equally often on left and right sides of the display. When legibility was reduced by dimming the digit, the more legible target was named on 69% of these trials; when legibility was reduced by brightening the grid, the more legible target was named on 73% of these trials.

In a fourth experiment, not yet complete, we are collecting data under better controlled conditions, in anticipation of further fitting and testing of alternative models. We are also comparing the procedure where the target is named when found to one in which the subject simply says "yes," to check generality over a more common search procedure. And finally, we will cue a biased target location randomly from trial to trial, using a tone in the ear on the side of the high-probability location, to learn the extent to which a voluntary shift of attention combines with the effect on search order due to legibility.

2.9 New tests of stages in mental operations

Basic to the use of RT data in our ongoing studies of visual representation is the assumption that differences in RT as one varies the size of an array, for example, reflect differences in just the encoding and retrieval operations between probe and response, and don't depend on details of the process by which the response is executed, for example. More generally, we need to know about the validity of the frequently made assumption that experimental manipulations influence mental operations selectively. The simplest circumstances that justify such an assumption are those in which the processes between probe and response are organized into distinct stages, with one stage beginning when and only when the previous stage ends. An important source of evidence for such a stage mechanism over the past two

decades has been the finding of additive effects of experimental factors on mean RT. In recent years the stage model has been challenged, and it has been shown that there are other mechanisms that can also produce additive factor effects on the mean. This problem led to the development and application of some new tests. One of the four experiments to which these tests were applied (a flash-detection experiment) is one in which the allocation of attention over visual space was investigated, bringing the work close substantively, as well as methodologically, to issues that are central to our research objectives. The work can be summarized as follows:

In the additive-factor method (Sternberg, 1969), for interpreting RT data from factorial experiments, additivity of the effects of experimental treatments on mean RT is taken to suggest that the underlying mechanism can be divided into independently changeable, serially arranged operations (*stage model*). In this project we considered two other explanations of additive means: a model with independently changeable alternate pathways (the *alternate-pathways model*), and the McClelland-Ashby *cascade model*. In all three models, experimental factors that influence different operations can have additive effects on mean RT. To choose among these models we develop several tests, including comparisons of entire RT distributions. Applied to the results of four diverse experiments, the tests support the stage model and contradict the alternate-pathways and cascade models. In particular, the results of one distributional test, the *summation test*, based on a suggestion by Ashby and Townsend (1980), support the stage model remarkably well.

Our tests of the cascade model incorporated some new ideas about testing complex models: We start by selecting statistics that seem likely to reveal limitations of the model. All possible values of these statistics then define a *statistic space*; by ranging over the entire parameter space of the model we cause the model to define allowed and forbidden regions in this statistic space. (The model can generate any point in the allowed region but no points in the forbidden region.) Given data from an experiment, the same statistics computed on these data define a point in the statistic space. The test of the model then involves determining whether this point falls in the forbidden or allowed region.

However, we feel that the most important contribution of this project are the development and applications of the summation test for testing the stage model. This test is applied to data from a 2 *x* 2 factorial experiment. Suppose factors A and B with levels A_i $(i=1,2)$ and B_j $(j=1,2)$, and let T_{ij} represent a reaction time from a condition in which factor A is at level A_i and factor B is at level B_j. In the stage model under test, we assume stages a (influenced selectively by factor A) and b (influenced selectively by factor B), with durations T_{ai} and T_{bj}, respectively, and we assume that $T_{ij} = T_{ai} + T_{bj}$. To arrive at the summation test we strengthen the model, by adding the assumption that the stage durations T_{ai} and T_{bj} are stochastically independent; we use *SIstage model* to denote this strengthened model.

The SIstage model then implies

$$F_{T_{11}+T_{22}}(t) = F_{T_{12}+T_{21}}(t), \quad (t \geq 0),$$

which asserts the stochastic equality of the two sums: $T_{11}+T_{22}$ and $T_{12}+T_{21}$, where $F_X(t) \equiv F_X$ is the cumulative distribution function (CDF) of the random variable X. In the summation test, one creates samples from $T_{11}+T_{22}$ and $T_{12}+T_{21}$ by simply summing RTs from each of the two pairs of conditions, and then determines the empirical CDFs of the two sums. To avoid losing information, we accomplish the summation by using the *cartesian-product sum*, in which all possible pairs of observations from the T_{11} and T_{22} samples (for example), are summed. Because the resulting summation distributions $F_{T_{11}+T_{22}}(t)$ and $F_{T_{12}+T_{21}}(t)$ must be identical (except for sampling error) given the SIstage model, any arbitrary property of the distributions must be identical.

To strengthen the summation test since Publication (1) we have extended the search for differences between $F_{T_{11}+T_{22}}(t)$ and $F_{T_{12}+T_{21}}(t)$ to histograms and density estimates, to supplement what we had already done for CDFs, and we have fitted orthogonal polynomials to the CDF differences to render the tests independent. These new tests strengthen our conclusions favoring the stage model. We have also explored the sensitivity of the summation test to violations of the stage model by applying it to data that simulate the alternate-pathways model, thereby introducing stochastic dependence of stage durations. In an attempt to be realistic we created the simulations by modifying data from actual experiments. The summation test failed dramatically for all of the three simulations we attempted. These results show that

our procedures are sensitive to at least one type of violation of the SIstage model of a size that might be observed in actual experiments.

To improve our sensitivity in comparing distributions we have also devised a new statistical test, called the "signruns" test, in which we compare the number of runs of positive and negative differences between the two distributions being compared, to the number for two distributions that make use of the same basic data, but are defined so as to be samples from the same population. (The reason that conventional tests cannot be used, aside from their insensitivity in some cases, is that they depend on the assumption that the two distributions being compared consist of independent samples from their respective populations; this is not the case for our convolutions, given the way in which we compute them, which is desirable for other reasons.)

2.10 Coordinate frame for visual attention

As mentioned in Section 2.4, one possibility for the transformation of visual information over time is a change in the coordinate system to which it is referred. Any procedure in which information is probed by its spatial location must take such changes into account, as must any procedure in which the display may change or the eyes may move between the cueing of attention and the extraction of information from a visual display. A new target-discrimination paradigm has been developed to determine the relative importance, at different delays after an attentional cue, of retinotopic, spatiotopic, and object-centered frames of reference. This paradigm is likely to form the basis of Teresa Pantzer's PhD thesis research.

2.11 Software and hardware for efficient experimentation

One of the most time-consuming parts of preparing a typical visual information processing experiment is writing the necessary software for stimulus preparation and experiment running. During the last half of the grant period we have reduced development time by roughly 50%. This increased efficiency is largely a result of an effort to create a library of experiment-independent software and a vastly improved host environment. Experiment running software should be correct and easy to modify for succeeding experiments. Creating a library of experiment-independent software attacks both of those problems. Similarly, our tools for initial data analysis have been much improved, which for example makes exploratory work relatively efficient, as well as monitoring subject performance from day to day to aid in adjusting experimental conditions.

Early in the grant period, all development work was done on ASCII terminals and a DEC MicroVax II running a 1985 version of Ultrix. Much of the development work is now done on a network of Sun SPARCstations and X-terminals. We have seen enormous benefits of reliable hardware, modern development tools, windowing systems, and greatly improved performance.

3. Publications

Under each item the relevant project or projects are indicated; references are to sections of the present report.

Published:

Roberts, S. & Sternberg, S. The meaning of additive reaction-time effects: Tests of three alternatives. In D. E. Meyer & S. Kornblum (Eds.) *Attention and Performance XIV: Synergies in Experimental Psychology, Artificial Intelligence, and Cognitive Neuroscience - A silver Jubilee.* Cambridge, MA : M.I.T. Press, 1993. Pp. 611-653.

Section 1.9.

In draft form:

(2) Pantzer, T., Sternberg, S. & Lubin, J.
Serial and parallel encoding operations: Evidence from effects of two kinds of homogeneous visual degradation on whole report.
Likely journal: *Journal of Experimental Psychology: Human Perception and Performance.*

Section 2.7.

(3) Sternberg, S., Knoll, R. L., Turock, D. L., & Porter, R.
Short-term dynamics of visual representation: Direct access by spatial position.
Likely journal: *Journal of Experimental Psychology: Human Perception and Performance.*

Sections 2.1 - 2.5.

In preparation:
(4) Sternberg, S., & Roberts, S.
New evidence from reaction-time tasks for stages in mental operations. Likely journal: *Science.*

Section 2.7.

(5) Pantzer, T., Sternberg, S., & Porter, R.
Serial and parallel encoding operations: Evidence from two kinds of factorial degradation.
Likely journal: *Journal of Experimental Psychology: Human Perception and Performance.*

Section 2.7.

4. Principal Personnel

Under each person's name is the list of projects in which he or she was a principal participant; references are to sections of the present report.

(1) Ross W. Porter (Analyst/Programmer); Sections 2.1 - 2.8, 2.11.

(2) Teresa Pantzer (5th-year graduate student, psychology); Sections 2.7, 2.10.

(3) Peter Marvit (2nd-year graduate student, psychology); Section 2.8.

(4) Saul Sternberg (Principal investigator); Sections 2.1-2.9.

5. Meeting Papers

(1) Pantzer, T. & Sternberg, S. (1992). Parallel and serial operations in character identification. Presented at the 1992 annual meeting of the Psychonomic Society, November.

Section 2.7.

A transcript of the paper mentioned above is included as an appendix to the present report.

(2) Sternberg, S., Marvit, P., Porter, R., & Coriell, A. S. Guidance of visual search by relative legibility. Abstract to be submitted for the 1993 annual meeting of the Psychonomic Society.

Section 2.8.